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Van Thorre et al.

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(54) **PYROLYSIS OIL MADE WITH A MICROWAVE-TRANSPARENT REACTION CHAMBER FOR PRODUCTION OF FUEL FROM AN ORGANIC-CARBON-CONTAINING FEEDSTOCK**

(58) **Field of Classification Search**
USPC 201/19; 202/96; 422/186.01; 585/240, 585/242, 16; 44/307, 308; 423/445 R
See application file for complete search history.

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Primary Examiner — Nina Bhat

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(57) **ABSTRACT**

Related U.S. Application Data

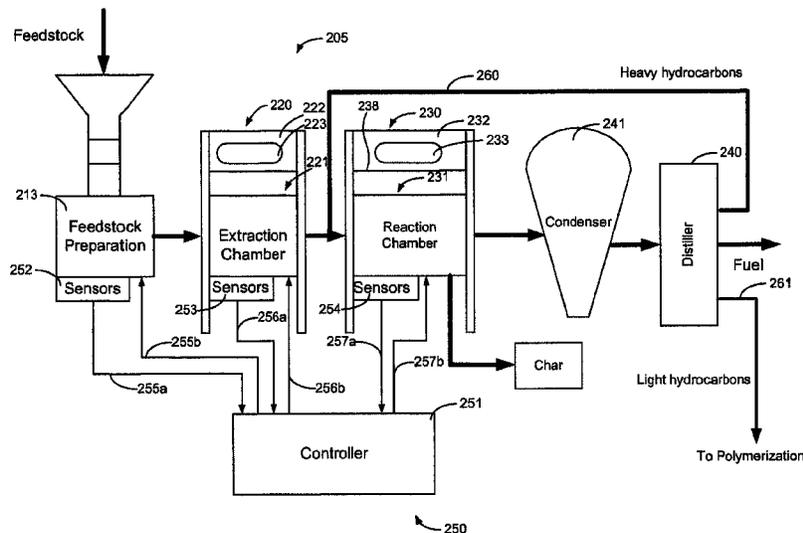
A pyrolysis oil composition by an oxygen-starved microwave process from an organic-carbon-containing feedstock is described. Feedstock is introduced into a substantially microwave-transparent reaction chamber. A microwave source emits microwaves which are directed through the microwave-transparent wall of the reaction chamber to impinge on the feedstock within the reaction chamber. The microwave source may be rotated relative to the reaction chamber. The feedstock is subjected to microwaves until the desired reaction occurs to produce a fuel. A catalyst can be mixed with the feedstock to enhance the reaction process.

(63) Continuation-in-part of application No. 13/751,677, filed on Jan. 28, 2013, now abandoned, and a (Continued)

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B01J 19/12 (2006.01)
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13 Claims, 9 Drawing Sheets

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(Continued)



Related U.S. Application Data

- continuation-in-part of application No. 12/854,754, filed on Feb. 24, 2010, now Pat. No. 8,361,282.
- (60) Provisional application No. 61/233,694, filed on Aug. 13, 2009.
- (51) **Int. Cl.**
C10G 1/02 (2006.01)
C10G 1/10 (2006.01)
B01J 8/08 (2006.01)
C10G 1/08 (2006.01)
- (52) **U.S. Cl.**
 CPC . *C10G 1/08* (2013.01); *C10G 1/10* (2013.01);
B01J 2208/00442 (2013.01); *B01J 2219/00006*
 (2013.01)

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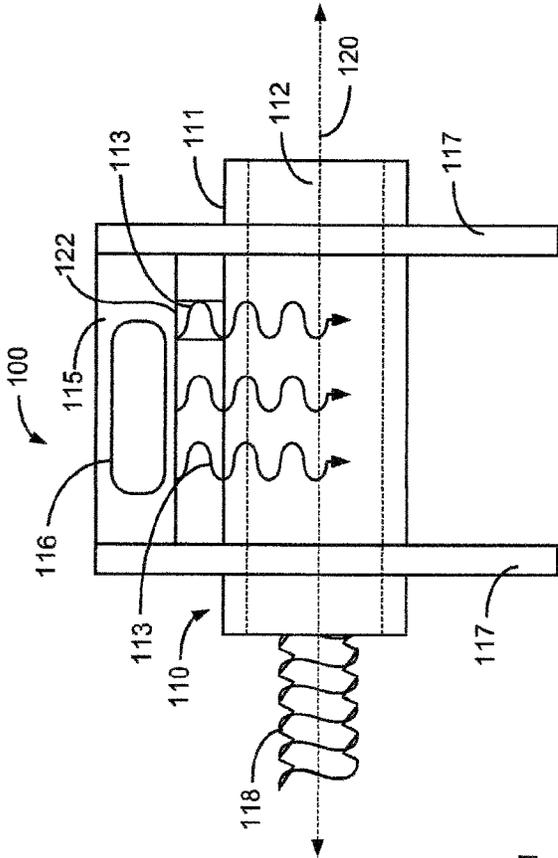


Figure 1A

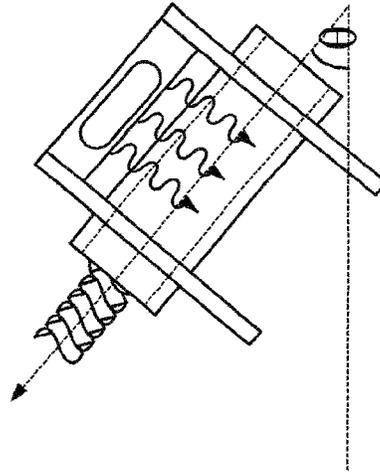


Figure 1C

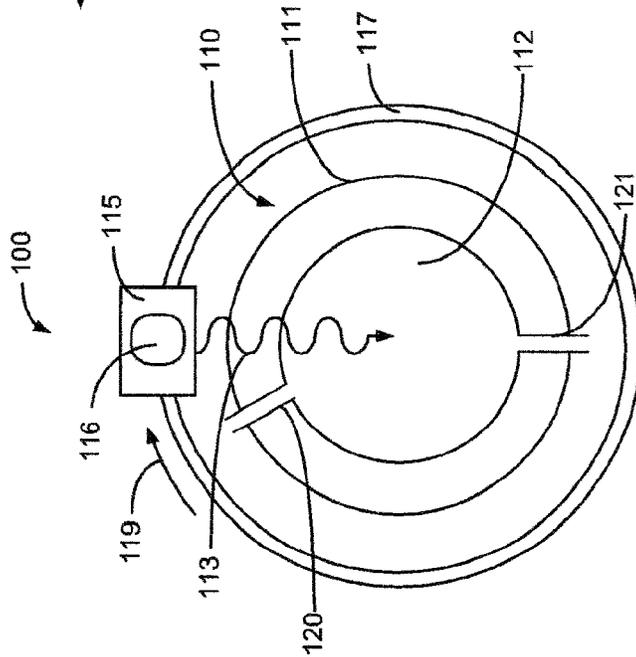


Figure 1B

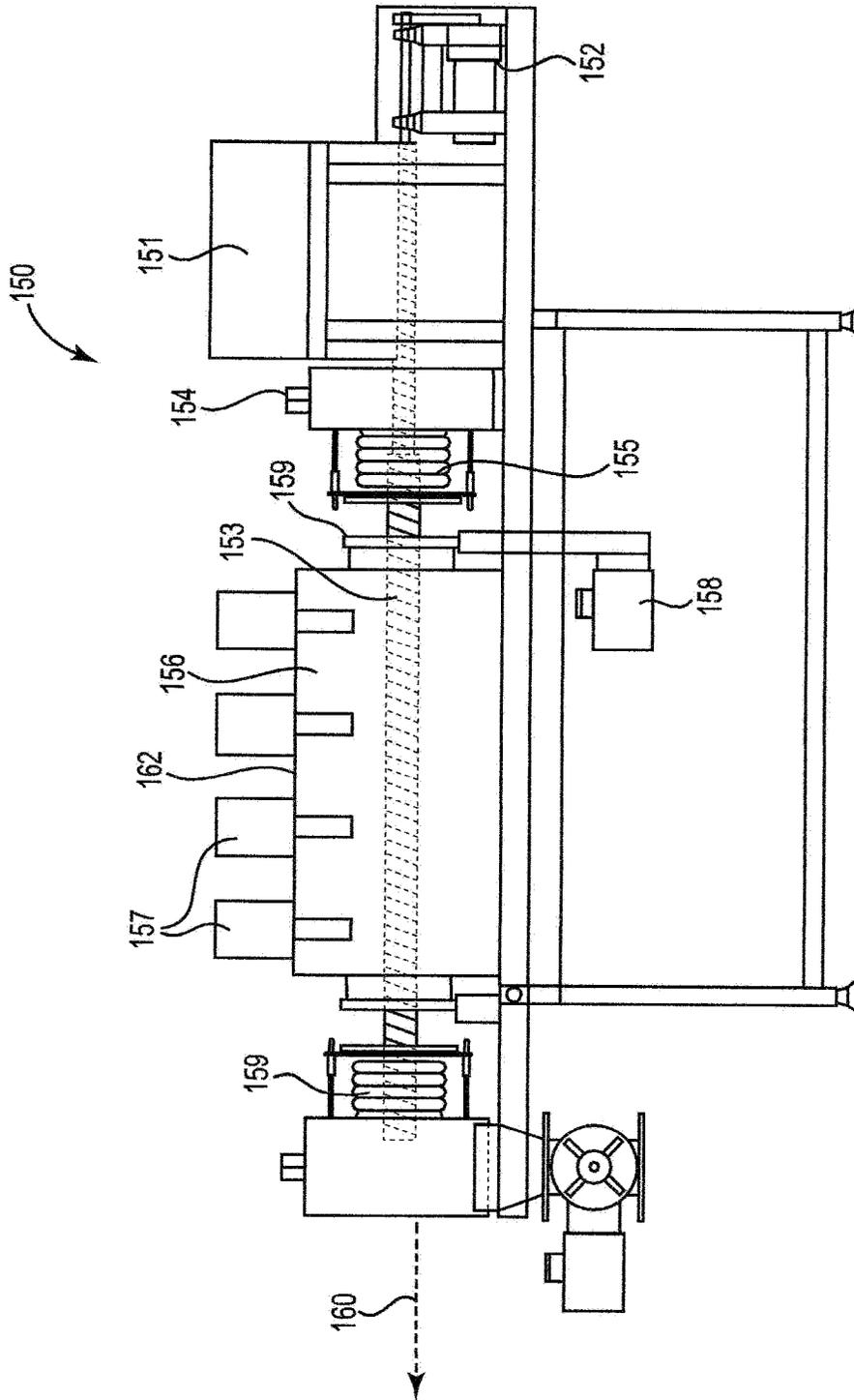


Figure 1D

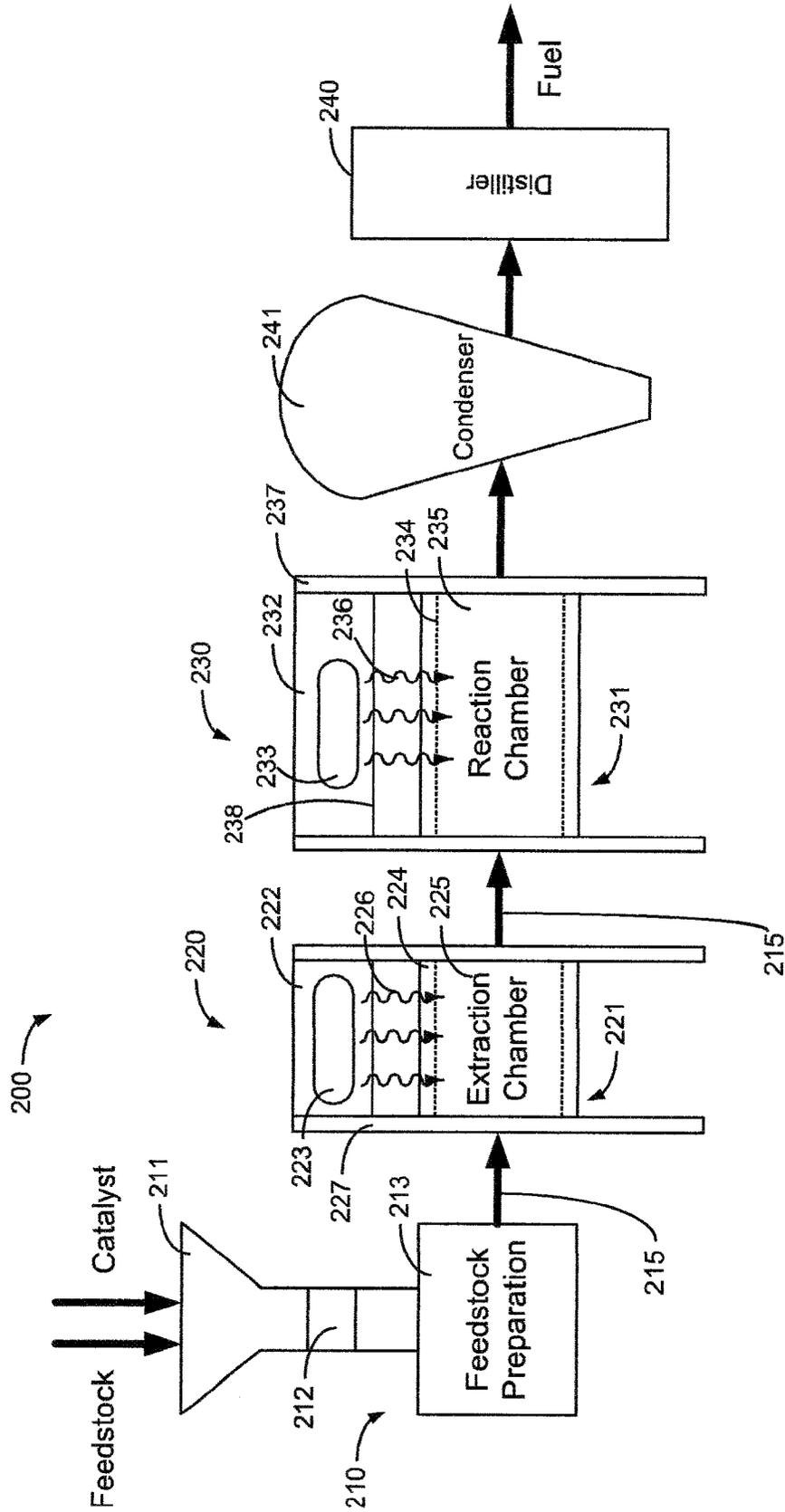


Figure 2A

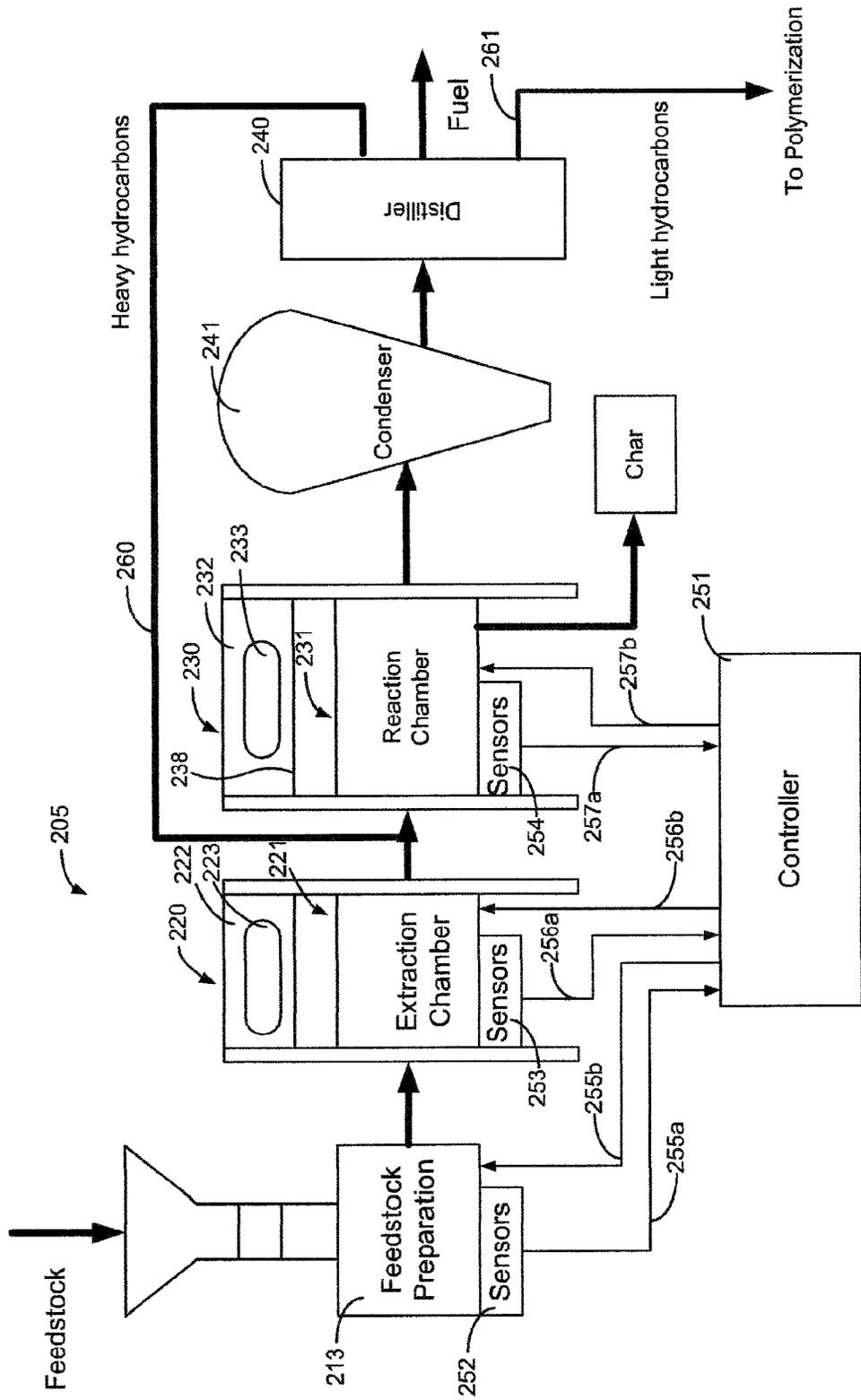


Figure 2B

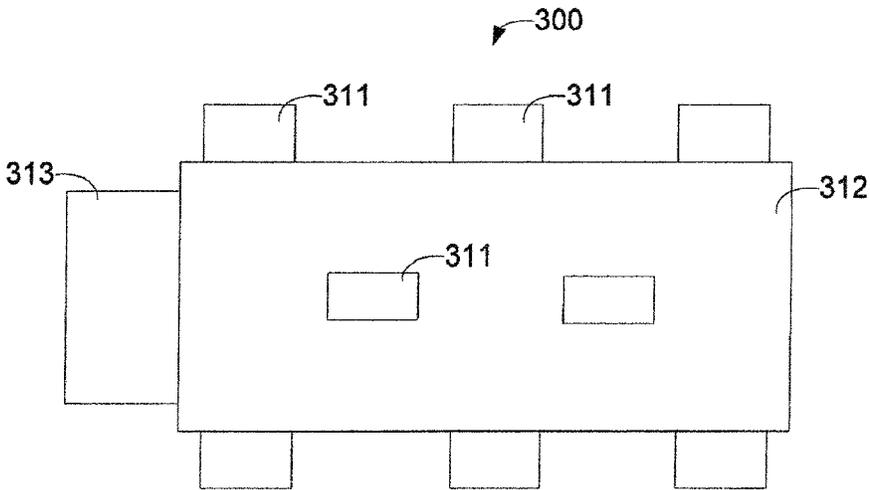


Figure 3A

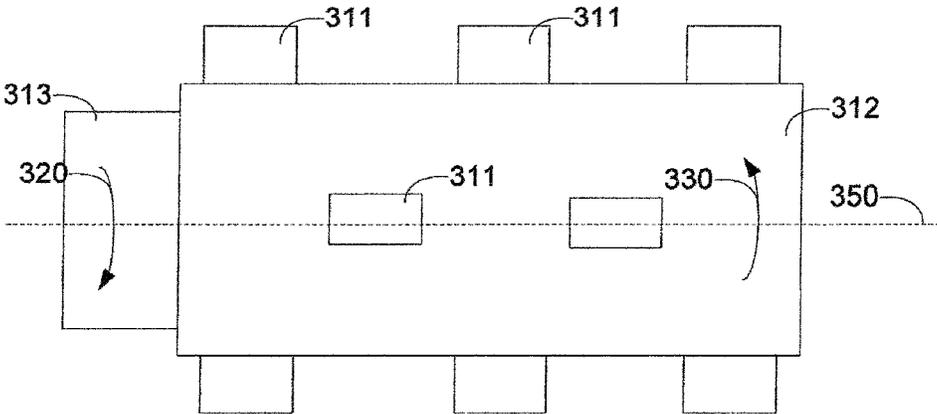


Figure 3B

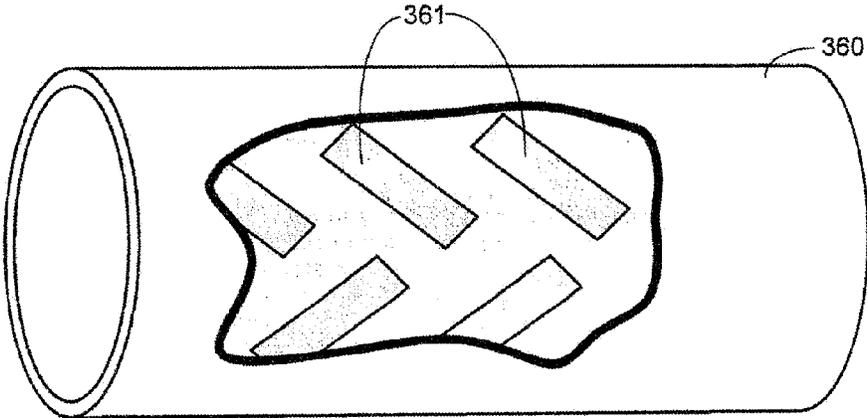


Figure 3C

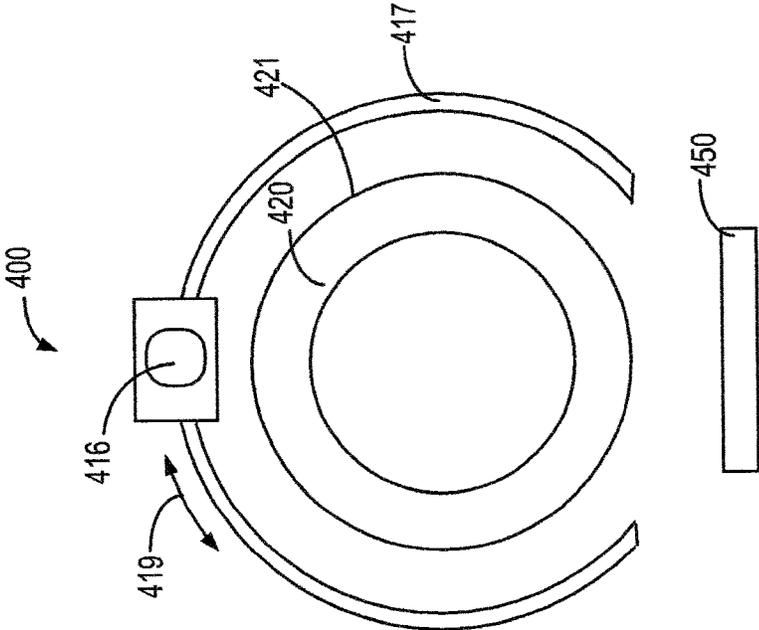


Figure 4

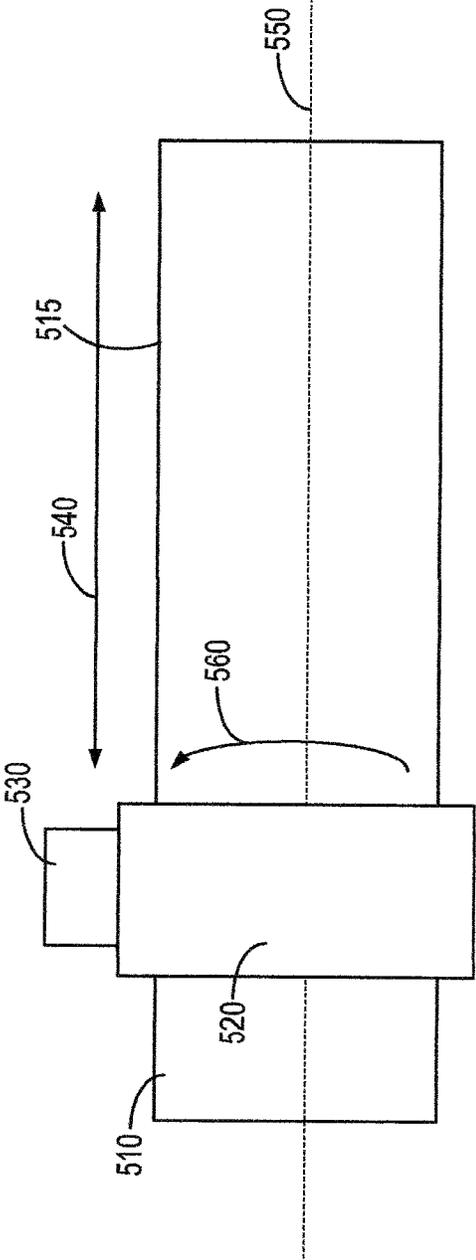


Figure 5

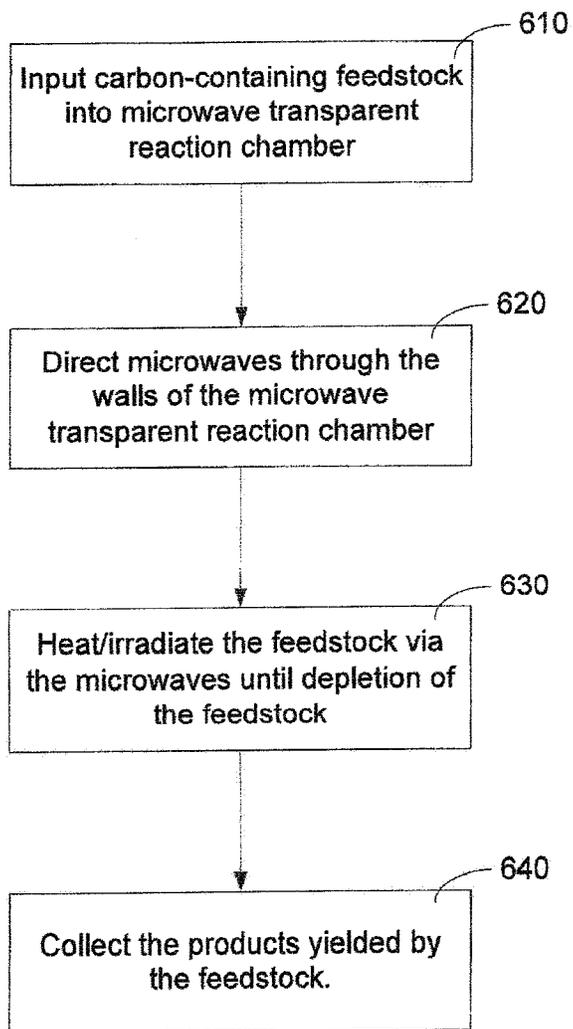


Figure 6

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**PYROLYSIS OIL MADE WITH A
MICROWAVE-TRANSPARENT REACTION
CHAMBER FOR PRODUCTION OF FUEL
FROM AN
ORGANIC-CARBON-CONTAINING
FEEDSTOCK**

RELATED APPLICATION

This application is a continuation-in-part of U.S. patent application Ser. No. 13/751,677, filed Jan. 28, 2013, now abandoned a continuation-in-part of U.S. patent application Ser. No. 12/854,754, filed on Aug. 11, 2010 (now U.S. Pat. No. 8,361,282) both of which claim the benefit of Provisional Patent Application Ser. No. 61/233,694, filed on Aug. 13, 2009, to which priority is claimed pursuant to 35 U.S.C. §119(e) and which are hereby incorporated herein by reference in their entirety.

FIELD OF THE INVENTION

The present invention relates generally to the production of liquid fuel from an organic-carbon-containing feedstock.

BACKGROUND OF THE INVENTION

The vast majority of fuels are distilled from crude oil pumped from limited underground reserves. As the earth's crude oil supplies are depleted, the world-wide demand for energy is simultaneously growing. Over the next ten years, depletion of the remaining world's easily accessible crude oil reserves will lead to a significant increase in cost for fuel obtained from crude oil.

The search to find processes that can efficiently convert industrial waste, depleteable materials, and renewable materials to fuels and by products suitable for transportation and/or heating is an important factor in meeting the ever-increasing demand for energy. In addition, processes that have solid byproducts that have improved utility are also increasingly in demand.

Liquid products by process that have more beneficial properties are an important factor in meeting the ever-increasing demand for energy and food. The present invention fulfills these needs and provides various advantages over the prior art.

SUMMARY OF THE INVENTION

A pyrolysis oil composition made from an organic-carbon-containing feedstock that passes through a microwave process system is described. The system includes at least one reaction chamber within a microwave-reflective enclosure. The reactive chamber includes at least one microwave-transparent chamber wall and at least one reaction cavity within the reaction chamber configured to hold the organic-carbon-containing feedstock in an externally supplied oxygen free atmosphere. A microwave subsystem includes at least one device configured to emit microwaves when energized. The microwave device is positioned relative to the reaction chamber so that the microwaves are directed through the microwave-transparent chamber wall and into the reaction cavity. The system also includes a mechanism that provides relative motion between the microwave device and the reaction chamber. The pyrolysis oil composition includes substantially no free water. Also the pyrolysis oil composition has a specific gravity of less than 1.2.

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In another embodiment, the pyrolysis oil composition of the invention involves a microwave process for converting an organic-carbon-containing compound to liquid fuel and char. An organic-carbon-containing feedstock is input into a substantially microwave-transparent reaction chamber containing no externally supplied oxygen and within a microwave reflective enclosure. Microwaves are directed from a microwave source through walls of the reaction chamber to impinge on the feedstock. Relative motion is provided between the microwave-transparent reaction chamber and the microwave source. The feedstock is microwaved until the volatiles are vaporized and condensed to produce the pyrolysis oil and the char.

The above summary is not intended to describe the pyrolysis oil in every detail. Characteristics and benefits over known pyrolysis oil made by the thermal processing of the same organic-carbon-containing feedstocks, together with a more complete understanding of the invention, will become apparent and appreciated by referring to the following detailed description and claims taken in conjunction with the accompanying drawings.

As used herein:

“Char” means the solid product of the decomposition of “organic-carbon-containing feedstock”.

“Complex water” is water that is tied to the organic-carbon-containing material and includes, for example, interstitial water, cellular water, and azeotropic water or water in solution with another liquid.

“Free water” is water in organic-carbon-containing feedstock that is not tied to the organic-carbon-containing material.

“Organic-carbon-containing feedstock” means “renewable material feedstock” and “unrenewable material feedstock” containing organic carbon.

“Pyrolysis oil” means liquid product of the decomposition of “organic-carbon-containing feedstock”.

“Renewable material feedstock” means organic-carbon-containing feedstock from plant or animal material that can be renewed in less than 50 years, and includes such materials as, for example, grasses, agricultural plant waste, tree parts, and animal manure.

“Unrenewable material feedstock” means hydrocarbon-containing feedstock that includes manufactured material and depletable plant and animal material that cannot be renewed in less than 50 years, and includes such materials as, for example, rubber such as tire crumbs, plastics, municipal waste, crude oil, peat, and coal such as bituminous coal, and anthracite coal.

BRIEF DESCRIPTION OF THE DRAWINGS

FIGS. 1A and 1B illustrate side and cross sectional views, respectively, of a system configured to convert organic-carbon-containing materials to char in accordance with embodiments of the invention;

FIG. 1C is a diagram of a tilted reaction chamber system in accordance with embodiments of the invention;

FIG. 1D is a diagram of a side view of a reaction chamber system in accordance with embodiments of the invention;

FIG. 2A is a block diagram of a system that uses the reaction chamber systems illustrated in FIGS. 1A and 1B for water/air extraction and a reaction process in accordance with embodiments of the invention;

FIG. 2B illustrates a reaction system that includes feedback control in accordance with embodiments of the invention;

FIG. 3A shows system which includes multiple stationary magnetrons arranged on a drum that is disposed outside a cylindrical reaction chamber having one or more micro-wave-transparent walls;

FIG. 3B illustrates a system having a drum supporting magnetrons which may be rotated around the longitudinal axis of the reaction chamber while the reaction chamber is concurrently rotated around its longitudinal axis;

FIG. 3C shows a reaction chamber with a feedstock transport mechanism comprising baffles;

FIG. 4 illustrates a system having a rotating magnetron in addition to a secondary heat source;

FIG. 5 depicts a system wherein a magnetron is moved along the longitudinal axis of the reaction chamber and is rotated around the longitudinal axis of the reaction chamber;

FIG. 6 is a flow diagram of a process for generating liquid fuel from organic-carbon-containing feedstock in accordance with embodiments of the invention.

While the invention is amenable to various modifications and alternative forms of the process, specifics thereof have been shown by way of example in the drawings and will be described in detail below. It is to be understood, however, that the intention is not to limit the invention to the particular process embodiments described. On the contrary, the invention is intended to cover product from all modifications, equivalents, and alternatives falling within the scope of the invention as defined by the appended claims.

DETAILED DESCRIPTION OF VARIOUS EMBODIMENTS

As supplies of easily reached petroleum dwindle, efforts increase to find alternatives, preferably renewable alternatives. Pyrolysis oil is the liquid product of the decomposition of organic-carbon-containing feedstocks that has been under investigation as a substitute for petroleum. Efforts to extract it from biomass, a biological material derived from living or recently living organisms, have resulted in a kind of liquid oil that normally contains too high levels of oxygen to be a hydrocarbon useful in a distillation processes to make specific hydrocarbon liquids and gases. Present methods to extract pyrolysis oil from organic-carbon-containing feedstock involves the thermal, chemical and biochemical methods for the destructive distillation of dried biomass in a reactor at temperature of about 500° C. with subsequent cooling.

In pyrolysis oil made by thermal heat or infrared radiation (IR), the radiation is absorbed on the surface of any feedstock and then is re-radiated to the next level at a lower temperature. This process is repeated over and over again until the IR radiation penetrates to the inner most part of the feedstock. All the material in the feedstock absorbs the IR radiation at its surfaces and different materials that make up the feedstock absorb the IR at different rates. A delta temperature of several orders of magnitude can exist between the surface and the inner most layers or regions of the feedstock. This variation in temperature may appear in a longitudinal direction as well as radial direction depending on the characteristics of the feedstock, the rate of heating, and the localization of the heat source. This variable heat transfer from the surface to the interior of the feedstock can cause cold and hot spots, thermal shocks, uneven surface and internal expansion cracks, fragmentation, eject surface material and create aerosols. All of this can result in microenvironments that cause side reactions with the creation of many different end products. These side reactions

are not only created in the feedstock but also in the volatiles that evaporate from the feedstock and occupy the air space in the internal reactor environment before being condensed and collected.

A common IR radiation process, pyrolysis, produces biochar, liquids, and gases from biomass by heating the biomass in a low/no oxygen environment. The absence of oxygen prevents combustion. The relative yield of products from pyrolysis varies with temperature. Temperatures of 400-500° C. (752-932° F.) produce more char, while temperatures above 700° C. (1,292° F.) favor the yield of liquid and gas fuel components. Pyrolysis occurs more quickly at the higher temperatures, typically requiring seconds instead of hours. Typical yields are 60% pyrolysis oil, 20% char, and 20% syngas, a fuel gas mixture consisting primarily of hydrogen, carbon monoxide, and very often some carbon dioxide, having significantly less energy content than natural gas, and commonly used in the operation of gas turbines to make electricity. High temperature pyrolysis is also known as gasification, and produces primarily syngas. By comparison, slow pyrolysis can produce substantially more char, on the order of about 50%.

In contrast, the process to make the pyrolysis oil of the invention uses microwave radiation from the oxygen-starved microwave process system described herein. With microwave radiation, almost all of the feedstock is nearly transparent to the microwave radiation. Most of the microwave radiation just passes through the entire feedstock because it isn't absorbed. Almost all materials are nearly transparent to microwave radiation except water molecules and other similar molecular bonds to water. So any feedstock subjected to the microwave radiation field is exposed to the radiation evenly, inside to outside, no matter what the physical dimensions and content of the feedstock. With microwaves, the radiation is preferentially absorbed by water molecules that then vibrate and heat up. The water molecules have so much entropy that the microwaves are selectively absorbed by the water. This heat is then transferred to the surrounding environment resulting in the feedstock being evenly and thoroughly heated.

When the water is all evaporated then some of the microwaves start to be absorbed by the remaining feedstock and heat up within a reflecting enclosure that cause the microwave radiation to pass through the feedstock numerous times until absorbed. Microwave radiation can complete the conversion of feedstock at lower temperatures than IR and shorter timeframes. Operating temperature reductions may range from 10-30% lower and heating times may be reduced from by a quantity equal to one-half to one-tenth of that needed by IR radiation to accomplish a similar degree of decomposition of a specified feedstock. All this can result in an evenly heated feedstock from the inside out so there are reduced microenvironments, less side reactions and cleaner volatiles to collect.

The atmosphere in the reaction chamber is free of externally supplied oxygen. In some embodiments, the atmosphere is inert, such as, for example, nitrogen. In some embodiments, the atmosphere may contain a small amount of water that previously had not been completely removed from the organic-carbon-containing feedstock being processed before it entered the reaction chamber.

The resulting pyrolysis oil from the microwave process system discussed herein is the disassociated carbon of an irradiated organic-carbon-containing hydrocarbon feedstock that has condensed into a liquid. The microwave system discussed herein can process organic-carbon-containing feedstock that does not contain water when it enters the

reaction chamber. All organic-carbon-containing feedstocks contain molecules that decompose in the reaction chamber with the more divalent bonds preferentially adsorbing more microwave energy to create heat. However, the conversion is more efficient, i.e., faster and at lower temperatures, when water or water-associated molecules are present. Some efficient conversions occur when the water content in the organic-containing feedstock as it enters the reaction chamber is at least 5 percent by weight and less than 15 percent by weight. Some occur when the water is at least 6 percent by weight and less than 12 percent by weight. For purposes of this document, water includes free water and complex water. Free water is water in organic-carbon-containing feedstock that is not tied to the organic-carbon-containing material. Complex water is water that is tied to the organic-carbon-containing material and includes, for example, interstitial water, cellular water, and azeotropic water or water in solution with another liquid. During the early exposure of the feedstock to the microwaves, the uniform heating of the water throughout the volume of the feedstock particles results in the creation of more numerous and more uniform pores. Because, most organic-carbon-containing feedstocks contain water the below discussion will focus on those feedstocks. However, similar results may occur less efficiently for those not containing water.

The pyrolysis oil made with the microwave radiation of the process has several improved characteristics when compared to a similar feedstock that is processed with IR radiation as discussed above. In general, it is more like petroleum in its distillation behavior, containing minimal oxides, water, corrosive impurities, and undesirable contaminants such as tar, a thicker hydrocarbon associated with hydrocarbons with chains of over C_{24} . First, because most of the free water is removed evenly from the surface to the center of the organic-carbon-containing feedstock, this free water does not then mix with the pyrolysis oil, only to next have to be removed by further processing to be a useful distillation feedstock. In addition, organic-carbon-containing feedstocks that contain lignin experience a better conversion of the lignin to pyrolysis oil with the desirable properties discussed below because the lignin is more dehydrated in the microwave process discussed herein.

Because the pyrolysis oil has significantly less oxygen content, the specific gravity is less than 1.2 or lower than that of pyrolysis oil made with similar feedstock by an IR process and is dependent on feedstock. Specific gravity of pyrolysis oil by the oxygen-starved microwave process of this disclosure is less than 1.2 and greater than 1.05 compared to that of a thermal process of over 1.2 and under 1.3. Some embodiment of the pyrolysis oil of the invention have a specific gravity of less than 1.2, some of less than 1.15, and some of less than 1.1. For reference, the specific gravity of water is 1.0 and diesel fuel is 0.8. Some embodiments of the pyrolysis oil have a specific gravity that is at least 0.1 less than it would have been in a pyrolysis oil composition made with the same feedstock but using a thermal process that creates a liquid phase during the process, some embodiments at least 0.15 less, and some at least 2.0 less. Also, some embodiments of the pyrolysis oil of the invention have an oxygen content that is at least 20 percent less than that made with the same feedstock by an IR process.

Second, the pyrolysis oil of the invention has lower acid content than that made with the same feedstock by an IR process. As a result, the pyrolysis oil of the invention is more stable, less corrosive, and less reactive to various other components in the pyrolysis oil than the pyrolysis oil made with the same feedstock by an IR process. The pH of

pyrolysis oil made with the microwave process disclosed herein typically ranges from 3.0 to 4.0 and is dependent on feedstock. Pyrolysis oil made by an IR process has a pH of between 0.5 and 2.5 for similar feedstocks. In some embodiments, the pyrolysis oil made with the oxygen-starved microwave process disclosed herein as a pH of at least 3.0, in some at least 3.2, in some at least 3.4, some at least 3.6, and in some at least 3.8.

Third, the pyrolysis oil of the invention has less undesirable impurities such as higher molecular weight tar and char particles that are common in pyrolysis oil made with an IR process. Because of the uniform conditions in an oxygen-starved atmosphere, the pyrolysis oil contains less char particles than pyrolysis oil made with the same feedstock by an IR process. Some embodiments of the pyrolysis oil of the invention have at least 50 percent by weight less char particles, some embodiments have at least 60 percent less, some embodiments have at least 70 percent less, and some embodiments have at least 80 percent less. For similar reasons, the pyrolysis oil contains less tar than pyrolysis oil made with the same feedstock by an IR process. Some embodiments of the pyrolysis oil of the invention have at least 30 percent by weight less tar, some embodiments have at least 40 percent less, some embodiments have at least 50 percent less, and some embodiments have at least 60 percent less.

Organic-carbon-containing feedstock can be separated into two categories, nonrenewable and renewable. Both produce superior pyrolysis oil by use of the oxygen-starved microwave process disclosed herein. For purposes of this document, non-renewable feedstock is organic-carbon-containing feedstock that is manufactured material and/or depletable plant and animal material that cannot be renewed in less than 50 years. Some require many decades to renew, some require many centuries to renew, some require many millennia or longer to renew and some may never be renewed because they are manufactured. This category can include such materials as, for example, rubber such as tire crumbs, plastics, municipal waste, crude oil, peat, and coal such as bituminous coal and anthracite coal. Pyrolysis oil made from non-renewable feedstock is referred to as pyrolysis oil in this document. Renewable feedstock is an organic-carbon-containing feedstock from plant or animal material that can be renewed in less than 50 years. Some can be renewed in less than a few decades, some can be renewed in less than a few years, and some can be renewed in less than a few months. This category can include such materials as, for example, grasses, agricultural plant waste, tree parts, and animal manure. Pyrolysis oil made from renewable feedstock is referred to also as pyrolysis oil in this document although other unsuccessful attempts to make pyrolysis oil of a satisfactory quality on the order of petroleum for fuel distillation purposes from renewable organic-carbon-containing feedstock have used terms like bio-oil. Organic-carbon-containing feedstock used to make the pyrolysis oil of the invention can contain mixtures of more than one renewable feedstock, mixtures of more than one non-renewable feedstock, or mixtures of both renewable and non-renewable feedstocks.

The composition by process invention comprises a pyrolysis oil composition made from an organic-carbon-containing feedstock that passes through a microwave process system is described. The system includes at least one reaction chamber within a microwave reflective enclosure and comprising at least one microwave-transparent chamber wall and a reaction cavity configured to hold the organic-carbon-containing feedstock in an externally supplied oxy-

gen free atmosphere. A microwave subsystem includes at least one device configured to emit microwaves when energized. The microwave device is positioned relative to the reaction chamber so that the microwaves are directed through the microwave-transparent chamber wall and into the reaction cavity. The system also includes a mechanism that provides relative motion between the microwave device and the reaction chamber. The pyrolysis oil composition includes substantially no free water. Also the pyrolysis oil composition has a specific gravity of less than 1.2 that is substantially 10 percent more than would have been for a pyrolysis oil composition made with the same feedstock but using a thermal process that creates a liquid phase during the process. The characteristics of the feedstock and resulting pyrolysis oil composition have already been discussed above. The microwave process used to make the pyrolysis oil of the invention is now discussed.

In the following description of the illustrated embodiments, references are made to the accompanying drawings that help to illustrate various embodiments of the microwave process used to make the pyrolysis oil of the invention. It is to be understood that other embodiments of the process may be utilized and structural and functional changes may be made without departing from the scope of the present invention.

The following description relates to approaches for processing solid or liquid organic-carbon-containing feedstock into pyrolysis oil by microwave enhanced reaction depolymerization processes that are suitable as a petroleum substitute in the subsequent distillation production of liquid fuels, e.g., diesel fuels, gasoline, kerosene, etc. Depolymerization, also referred to as "cracking", is a refining process that uses heat to break down (or "crack") hydrocarbon molecules into shorter polymer chains which are useful as fuels. Depolymerization may be enhanced by adding a catalyst to the feedstock which increases the speed of the reaction and/or reduces the temperature and/or the radiation exposure required for the processes. Furthermore, the catalyst, such as zeolite, has a nanostructure which allows only molecules of a certain size to enter the crystalline grid or activate the surface areas of the catalyst and to interact with the catalyst. Thus, the catalyst advantageously is very effective at controlling the product produced by the reaction processes because only substances having a specified chain length may be produced using the catalytic process. Catalytic depolymerization is particularly useful for transforming biomass and other organic-carbon-containing feedstock into fuels useable as transportation or heating fuels.

One aspect of efficient depolymerization is the ability to heat and irradiate the feedstock substantially uniformly to the temperature that is sufficient to cause depolymerization as well as activate the catalyst. Upon depolymerization, long hydrocarbon chains "crack" into shorter chains. Microwave heating has been shown to be particularly useful in heating systems for thermal depolymerization. Heating systems such as flame, steam, and/or electrical resistive heating, heat the feedstock by thermal conduction through the reaction chamber wall. These heating systems operate to heat the feedstock from the outside of the reaction chamber walls to the inside of the feedstock, whereas microwaves heat from the inside of the feedstock toward the reaction chamber walls. Using non-microwave heating sources, the heat is transferred from the heat source outside wall to the inside of the vessel wall that is in direct contact with the feedstock mixture. The heat is then transferred to the surfaces of the feedstock and then transferred, again, through the feedstock until the internal

areas of the feedstock are at a temperature near the temperature of the reaction chamber wall.

One problem with this type of external heating is that there are time lags between vessel wall temperature transmission and raising the feedstock temperature that is contained in the center of the vessel as well as the internal area of the feedstock matrix. Mixing the feedstock helps to mitigate these conditions. Still, millions of microenvironments exist within the reactor vessel environment and the feedstock particles themselves. This causes uneven heat distribution within the reaction chamber of varying degrees. These variant temperature gradients cause uncontrollable side reactions to occur as well as degradation of early conversion products that become over-reacted because of the delay in conversion reaction timeliness. It is desirable to produce and retain consistent heating throughout the feedstock and the reaction products so that good conversion economics are achieved and controllable. Microwave heating is an efficient heating method and it also serves to activate catalytic sites.

Embodiments of the invention are directed to a reaction chamber system that can be used to process any organic-carbon-containing feedstock, whether solid and/or liquid, to extract the volatile organic compounds in the feedstock at a temperature range that will produce liquid pyrolysis oil that can be further processed efficiently into transportation fuels.

Microwaves are absorbed by the water molecules in the material that is irradiated in the microwave. When the water molecules absorb the microwaves, the molecules vibrate, which creates heat by friction, and the heat is convected to the surrounding material.

The reason microwaves are absorbed by water molecules is specific to the covalent bonds that attach the hydrogen to the oxygen in a water molecule. The oxygen atom in water has a large electronegativity associated with it due to the size of its nucleus in comparison to the hydrogen atom and the electrons from the two hydrogen atoms are drawn closer to the oxygen atom. This gives this end of the molecule a slight negative charge and the two hydrogen atoms then have a slight positive charge. The consequence of this distortion is that the water molecule acts like a small, weak magnet. The dipole feature of the water molecule allows the molecule to absorb the microwave radiation and starts it vibrating like a guitar string. The vibration of the bonds causes friction that turns to heat and then convects out into the irradiated material.

To take advantage of this feature of microwave radiation, a reaction chamber system described herein takes advantage of microwave irradiation and heating in processing feedstock that contains carbon and can be converted to transportation fuels. The reactor may be made from a substantially microwave transparent substance such as quartz, a glass-like material that is substantially transparent to microwave radiation. Because quartz can be manipulated into many shapes, it provides design discretion for shaping the reaction chamber, but in one example the reaction chamber is configured in the shape of a tube or cylinder. The cylindrical shape allows for the feedstock to feed in one end and exit at the opposite end. An example of a suitable reaction chamber would be a quartz tube that is about four feet (1.2 meters) long with a wall thickness of about $\frac{3}{16}$ inch (4.8 mm).

The microwave reaction chamber is surrounded by a microwave reflective enclosure. This causes the microwave radiation to pass repeatedly through the reaction chamber and devolatilize the organic-carbon-containing feedstock after the water, if present, is evaporated and driven off. The

microwave reflective enclosure is any that reflects microwaves. Materials include, for example, sheet metal assembled as Faraday cages that are known to the art.

Microwave radiation is generated by a magnetron or other suitable device. One or more microwave producing devices, e.g., magnetrons can be mounted external to the quartz tube wall. Magnetrons come in different power ranges and can be controlled by computers to irradiate the processing feedstock with the proper energy to convert the feedstock to most desirable fuel products efficiently. In one application, the magnetron can be mounted on a cage that would rotate around the outside of the reactor tube as well as travel the length of the reactor tube. Feedstock traveling through the length of the inside of the tube will be traveling in a plug flow configuration and can be irradiated by fixed and/or rotating magnetrons. A computer may be used to control the power and/or other parameters of the microwave radiation so that different feedstock, with different sizes and densities can be irradiated at different parameter settings specific to the feedstock and thus convert the feedstock more efficiently.

These configurations of a reactor will allow efficient processing of feedstocks, from relatively pure feedstock streams to mixed feedstock streams that include feedstocks of different densities, moisture contents, and chemical make up. Efficiencies can occur because the fuel products are extracted from the reactor chamber as they are vaporized from the feedstock, but further processing of the remaining feedstock occurs until different fuel products are vaporized and extracted. For example, dense feedstock, such as plastics, take longer to process into a useable fuel than less dense feedstock, such as foam or wood chips. The system described herein continues to process dense feedstock without over-processing the earlier converted products from the less dense feedstock. This is accomplished by using both stationary and rotating microwave generators.

One example of a mixed feedstock would be unsorted municipal solid waste. In some implementations, catalyst may be added in the feedstock which helps in the conversion of the feedstock as well as the speed at which the conversion can progress. A catalyst can be designed to react at the preset processing temperature inside the reactor or to react with the impinging microwave radiation. In some embodiments, no catalyst is required. In other embodiments, the catalyst may be a rationally designed catalyst for a specific feedstock.

The plug flow configuration with the reactors described herein will allow adjustments to the residence time that the feedstock resides within the reactor core for more efficient exposure to the heat and the radiation of the microwaves to produce the desired end products.

Inlets and/or outlets, e.g., quartz inlets and/or outlets can be placed along the walls of the reaction chamber to allow for pressure and/or vacuum control. The inlets and outlets may allow the introduction of inert gases, reactive gases and/or the extraction of product gases.

Thus, the design of the microwave-transparent reaction chamber, the use of microwaves as a heating and radiation source with fixed and/or rotating magnetrons, plug flow processing control, with or without the use of catalysts, will allow the processing of any organic-carbon-containing feedstock.

A system in accordance with embodiments of the invention includes a reaction chamber having one or more substantially microwave-transparent walls and a microwave heating/radiation system. The microwave heating/radiation system is arranged so that microwaves generated by the heating/radiation system are directed through the substan-

tially microwave-transparent walls of the reaction chamber and into the reaction cavity where the feedstock material is reacted without substantially heating the walls of the reaction chamber. To enhance the temperature uniformity of the feedstock, the reaction chamber and the heating/radiation system may be in relative motion, e.g., relative rotational and/or translational motion. In some implementations, the heating system may rotate around a stationary reaction chamber. In some implementations, the feedstock within the reaction chamber may rotate by the use of flights with the heating/radiation system remaining stationary. In some implementations, the reaction chamber may rotate with the heating system remaining stationary. In yet other implementations, both the reaction chamber and the heating/radiation system may rotate, e.g., in countercurrent, opposing directions. To further increase temperature uniformity, the system may include a mechanism for stiffing and/or mixing the feedstock material within the reaction chamber. The reaction chamber may be tilted during reaction process, for example, to force the feedstock to go through the catalytic bed.

FIGS. 1A and 1B illustrate side and cross sectional views, respectively, of a system 100 for converting organic-carbon-containing feedstock to liquid pyrolysis oil and char in accordance with embodiments of the invention. Although the reaction chamber 110 may be any suitable shape, the reaction chamber 110 is illustrated in FIGS. 1A and 1B as a cylinder having a cylindrical wall 111 that is substantially transparent to microwaves in the frequency range and energy used for the reaction process. The reaction chamber 110 includes a reaction cavity 112 enclosed by the cylindrical wall 111. The system 100 includes a transport mechanism 118 configured to move the feedstock through the reaction chamber. The operation of the system 100 with regard to the reactions taking place within the reaction chamber 110 may be modeled similarly to that of a plug flow reactor.

As illustrated in FIG. 1A, system includes a transport mechanism 118 for moving the feedstock material through the reaction chamber 110. The transport mechanism 118 is illustrated as a screw auger, although other suitable mechanisms, e.g., conveyer, may also be used. The transport mechanism 118 may further provide for mixing the feedstock within the reaction chamber. In some embodiments, the reaction chamber wall 111 may have a thickness of about $\frac{3}{16}$ inch (4.8 millimeters). The smoothness of the reaction chamber wall 111 facilitates the movement of the feedstock through the reaction chamber 110.

A heating/radiation subsystem 115 may include any type of heating and/or radiation sources, but preferably includes a microwave generator 116 such as a magnetron which is configured to emit microwaves 113 having a frequency and energy sufficient to heat the organic-carbon-containing feedstock to a temperature sufficient to facilitate the desired reaction of the feedstock, for example, for depolymerization of the feedstock, microwaves in a frequency range of about 0.3 GHz to about 300 GHz may be used. For example, the operating power of the magnetrons may be in the range of about 1 Watt to 500 kilowatts. The magnetron 116 is positioned in relation to the reaction chamber 110 so that the microwaves 113 are directed through the wall 111 of the reaction chamber 110 and into the reaction cavity 112 to heat and irradiate the material therein. A mechanism 117 provides relative motion between the magnetron 116 and the reaction chamber 110 along and/or around the longitudinal axis 120 of the reaction chamber 110. In some embodiments, the mechanism 117 may facilitate tilting the reaction chamber 110 and/or the magnetron 116 at an angle θ (FIG. 1C) to

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facilitate the reaction of the feedstock and/or the extraction of gases, for example. In the embodiment illustrated in FIGS. 1A-C, the magnetron 116 is positioned on a rotational mechanism 117, such as a rotatable cage or drum that rotates the magnetron 116 around the stationary reaction chamber 110. In some implementations, the rotation around the chamber may not be complete, but the rotation path may define an arc around the circumference of the reaction chamber. The rotation may occur back and forth along the path of the arc. As previously mentioned, in some embodiments, the reaction chamber 110 may be the rotating component, or both the heating/radiation subsystem 116 and the reaction chamber 110 may rotate, e.g., in opposing, countercurrent directions. The rotation between the reaction chamber and the magnetron provides more even heating and more even microwave exposure of the feedstock within the reaction cavity 112, thus enhancing the efficient reaction chemistry of the feedstock and/or other processes that are temperature/radiation dependent, such as removal of water from the feedstock. The rotation lessens the temperature gradient and/or maintains a more constant microwave flux across the plug inside the reaction chamber.

The reaction chamber 110 may include one or more entry ports 120, e.g., quartz entry ports, configured to allow the injection or extraction of substances into or out of the reaction cavity 112. The reaction chamber 110 is also surrounded by a microwave-reflective enclosure 122. In one implementation, the quartz ports may be used to extract air and/or oxygen from the reaction cavity. Extraction of air and/or oxygen may be used to suppress combustion which is desirable for some processes.

For example, in certain embodiments, the system 100 may be used to preprocess the feedstock through compression and/or removal of air and/or water. In this application, gases such as hydrogen and/or nitrogen may be injected through one or more ports 120 to hydrogenate and/or suppress combustion of the feedstock. The reaction chamber 110 may also include one or more exit ports 121, e.g., quartz exit ports, configured to allow passage of water, water vapor, air, oxygen and/or other substances and/or by-products from the reaction chamber 110.

FIG. 1D is a diagram illustrating a reaction chamber system 150 for producing fuel from organic-carbon-containing feedstock in accordance with embodiments of the invention. The system 150 includes an input hopper (also referred to as a load hopper) 151 configured to allow introduction of the feedstock material into the system 150. A gearmotor auger drive 152 provides a drive system for the auger 153 that transports the feedstock through the system 150. As the feedstock is compressed in the load hopper 151, air is extracted through the atmosphere outlet 154. A seal 155 isolates the load hopper 151 from the reaction chamber 156 to maintain a level of vacuum. The reaction chamber 156 includes walls of a microwave-transparent material. One or more stationary microwave heads 157 are positioned at the walls of the reaction chamber 156. In addition, the system 150 includes one or more rotating microwave heads 158. In one implementation, each rotating microwave head is located at a fixed position with respect the longitudinal axis 160 of the reaction chamber 156. The rotating microwave head is mounted on a slipring bearing 159 which allows the microwave head 158 to rotate around the reaction chamber 156. A microwave reflective enclosure 162 encompasses the reaction chamber 156. In some implementations the rotating microwave head(s) 158 may rotate around the longitudinal axis 160 of the reaction chamber 156 as well as moving back and forth along the longitudinal axis 160. The system 150

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includes a seal at the exit of the reaction chamber 156 to maintain the reaction chamber vacuum.

FIG. 2A is a block diagram of a system 200 that uses one or more of the reaction chamber systems 100 illustrated in FIGS. 1A and 1B. The reaction chamber systems 220, 230 may be arranged and/or operated in series or in a parallel configuration. The extraction process 220 and the reaction process 230 depicted in FIGS. 2A and 2B are illustrated as occurring in two separate reaction chambers, e.g., that operate at different temperatures. Alternatively, the extraction process and the reaction process may be implemented in a single reaction chamber with two separate zones, e.g., two separate temperature zones.

In the system 200 of FIG. 2, one or both of the water/air extraction subsystem 220 and the reaction subsystem 230 may be similar to the reaction chamber system 100 of FIGS. 1A and 1B. Organic-carbon-containing feedstock, such as, for example, one or more of manure, wood chips, plant-based cellulose, tire crumbs, municipal solid waste, plastic, crude oil, peat and coal, enters the system through a hopper 211, and traverses an airlock 212 to enter a feedstock preparation module 213. If needed, a catalyst, such as zeolite, and/or other additives that enhance the reaction process, for example to adjust the pH, may be introduced into the system 200 through the input hopper 211 and/or the entry ports (shown in FIG. 1B). In the feedstock preparation module 213, the feedstock material is shredded to a predetermined particle size that may be dependent on the properties of the feedstock, such as the purity, density, and/or chemical composition of the feedstock. If used, the catalyst may be added at the time that the feedstock is being prepared so that the catalyst is evenly dispersed within the feedstock material before entering the reaction chamber 231. In general, the less uniform the feedstock, the smaller the particle size needed to provide efficient reaction.

After the initial feedstock preparation stage, the shredded and mixed feedstock is transported by a transport mechanism 215 into the extraction chamber 221 of the next stage of the process. The air/water extraction subsystem 220, which performs the optional processes of water and/or air extraction prior to the reaction process includes a heating/radiation module 222 comprising at least a magnetron 223 configured to generate microwaves 226 that may be mounted on a rotational or stationary mechanism 227. If mounted on a rotational mechanism, the mechanism rotates the magnetron 223 either partially or fully around the extraction chamber 221 as the microwaves 226 are directed through the wall 224 of the extraction chamber 221 and into the extraction cavity 225 impinging on and heating the feedstock therein. In some embodiments, the heating module 222 may utilize only one magnetron 223 or only two or more magnetrons without using other heat/radiation sources.

In some embodiments, the heating/radiation module 222 may utilize the magnetron 223 in addition to other heat sources, such as heat sources that rely on thermal conduction through the wall of the reaction chamber, e.g., flame, steam, electrical resistive heating, recycled heat from the process, and/or other heat sources. During the air and/or water extraction process, the feedstock may be heated to at least 100 C., the boiling point of water, to remove excess water from the feedstock. The excess water (e.g., in the form of steam) and/or other substances may exit the extraction chamber 221 via one or more exit ports. Additives to the feedstock, such as inert and/or reactive gases including hydrogen and/or nitrogen, may be introduced via one or more input ports into the extraction chamber 221 of the water/air extraction process. In addition to being heated and

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irradiated by microwaves, the feedstock may also be subjected to a pressurized atmosphere and/or a vacuum atmosphere and/or may be mechanically compressed to remove air from the extraction chamber 221.

After the optional air and/or water extraction process, the transport mechanism 215 moves the feedstock to the next processing stage 230 which involves the reaction process, e.g., thermal depolymerization, of the feedstock. After the feedstock/catalyst mixture enters the reaction chamber 231 surrounded by the microwave reflecting enclosure 238, the mixture is heated to a temperature that is sufficient to facilitate the desired reaction. For example a temperature of in a range of about 200 C. to about 350 C. is used to crack the hydrocarbons in the feedstock into shorter chains to produce pyrolysis oil through depolymerization. In addition to being heated, the feedstock may also be subjected to a pressurized atmosphere or a vacuum atmosphere, and/or may be mechanically compressed in the reaction chamber 231.

In some embodiments, heating/radiation in the reaction chamber 231 is accomplished using a magnetron 233 emitting microwaves 236. The magnetron 233 may rotate relative to the reaction chamber 231. As previously described in connection with the water extraction stage 220, the rotating magnetron 233 may be supported by rotational mechanism 237, such as a cage or drum. The rotational mechanism 237 allows relative rotational motion between the magnetron 233 and the reaction chamber 231. For example, the magnetron 233 may rotate completely around the reaction chamber 231 or the rotation of the magnetron 233 may proceed back and forth along an arc that follows the circumference of the reaction chamber 231. The rotating magnetron heating system 233 may be supplemented using a stationary magnetron, and/or other conventional heat sources such as a flame or electrical resistive heating. Rotating the magnetron 233 provides more even heating/radiation of the feedstock material and catalyst within the reaction cavity 235 and enhances the heating properties over that of stationary heat sources.

The cracked hydrocarbons vaporize and are collected in a condenser 241 and liquefy into pyrolysis oil and then are sent to the distiller 240 to produce products such as a diesel fuel or a cleaner pyrolysis oil composition, while heavier, longer chain hydrocarbon molecules such as tars and char particulates may be recycled back to the reaction chamber. In some implementations, distillation may not be necessary, and the fuel product only needs to be filtered and used as pyrolysis oil.

In some configurations, it is desirable to control the processes of the reaction to allow a higher efficiency of fuel extraction from the feedstock. FIG. 2B is a block diagram of a system 205 that includes the system components described in connection with FIG. 2A along with a feedback control system 250. The illustrated feedback control system 250 includes a controller 251 and one or more sensors 252, 253, 254 which may be configured to sense parameters at various stages during the process. The feedback control system 250 may include sensors 252 at the feedstock preparation stage which are configured to sense parameters of the feedstock and/or feedstock preparation process. For example, the sensors 252, may sense the chemical composition of the feedstock, density, moisture content, particle size, energy content or other feedstock parameters. The sensors 252 may additionally or alternatively sense the conditions within the feedstock preparation chamber, e.g., flow, pressure, temperature, humidity, composition of the gases present in the chamber, etc. The sensors 252 develop signals 255a which are input to the controller electronics 251 where they are

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analyzed to determine the condition of the feedstock and/or the feedstock preparation process. In response to the sensed signals 255a, the controller 251 develops feedback signals 255b which control the operation of the feedstock preparation module 213. For example, in some implementations, the controller 251 may control the feedstock preparation module 213 to continue to shred and/or grind the feedstock material until a predetermined particle size and/or a predetermined particle size variation is detected. In another example, based on the sensed chemical composition of the feedstock, the controller 251 may cause a greater or lesser amount of catalyst to be mixed with the feedstock or may cause different types of catalyst to be mixed with the feedstock.

The control system 250 may also develop feedback signals 256b, 257b to control the operation of the water extraction module 220 and/or the reaction module 230, respectively, based on sensed signals 256a, 257a. For example, the sensors 253, 254 may sense the temperature of the water extraction and/or reaction processes and the controller 251 may develop feedback signals 256b, 257b to control the operation of the heating/radiation systems 222, 232, e.g., power, frequency, pulse width, rotational or translational velocity, etc. of one or both of the magnetrons 223, 233. The controller 251 may develop feedback signals to the magnetrons to control the amount of radiation impinging on the feedstock so that the feedstock will not be over-cooked or under-cooked and development of hot spots will be avoided. The controller 250 may control the injection of various substances into one or both of the extraction chamber and/or the reaction chamber 221, 231 through the entry ports to control the processes taking place within the chambers 221, 231. Char, the residue of the depleted feedstock, is sent to a storage unit. In some embodiments, the controller 250 may be used to control conditions that beneficially affect the properties of the pyrolysis oil where specific properties are desired beyond that resulting just from the feedstock choice. After the distillation stage, the heavy hydrocarbons may be recycled back into the reaction chamber and the lighter hydrocarbons may be sent on to a polymerization stage or further distillation stage.

The reaction chambers may be made of quartz, glass, ceramic, plastic, and/or any other suitable material that is substantially transparent to microwaves in the frequency and energy range of the reaction processes. In some configurations, the heating/radiation systems described herein may include one or more magnetrons that rotate relative to the reaction chamber. In some embodiments, the magnetrons may be multiple and/or may be stationary. FIG. 3A illustrates system 300 which includes multiple stationary magnetrons 311 arranged on a drum 312 that acts as a Faraday cage and is disposed outside a cylindrical reaction chamber 313 having one or more microwave-transparent walls. In system 300, the drum is made of a material that is microwave opaque, such as, for example, metal, so as to cause the microwaves in the reaction chamber 313 to reflect back and forth through the feedstock, thus more efficiently being used to convert the feedstock into pyrolysis oil and char. The operation of the magnetrons may be continuous, or may be pulsed, e.g., in a multiplexed pattern. In some embodiments (FIG. 3B), the drum 313 supporting the magnetrons 311 may be rotated 330 around the longitudinal axis 350 of the reaction chamber 312 and/or the reaction chamber 312 may be rotated 320 around its longitudinal axis 350.

A feedstock transport mechanism may be disposed within the reaction chamber. For example, as illustrated in FIG. 3C, the feedstock transport mechanism may comprise one or more baffles 361 that are configured to move the feedstock

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through the reaction chamber **360** as the reaction chamber rotates. The baffles **361** may be mounted to the walls of the reaction chamber **360** and/or may be otherwise installed within the reaction chamber to provide movement of feedstock within and through the reaction chamber **360**, e.g., longitudinally through the reaction chamber.

In some embodiments, illustrated in FIG. **4**, one or more secondary heat sources **450**, such as a flame, steam, and/or electric resistive heating, or recycled heat, may be used in addition to magnetrons **416** which are stationary, or are supported on a mechanism **417** that rotates around the circumference of the reaction chamber **420** enclosed in a microwave-reflecting Faraday cage **421**. In some configurations, the magnetrons **416** may not make a complete revolution around the reaction chamber **420**, but may rotate back and forth **419** along an arc that follows the circumference of the reaction chamber **420**. Various configurations are possible as long as the feedstock is exposed to substantially uniform heat throughout the mass of the feedstock particles to form char having pore density, distribution, and variance in size and distribution as described above for char of the invention.

Movement of the one or more magnetrons relative to the reaction chamber may also include motion that moves the magnetron along the longitudinal axis of the reaction chamber, as illustrated in FIG. **5**. FIG. **5** illustrates a reaction chamber **510** and a cage **520** that supports a magnetron **530**. The cage **520** and magnetron **530** may be moved **540** back and forth along the longitudinal axis **550** of the reaction chamber **510** and over a metal microwave-reflecting Faraday cage **515** enclosing the reaction chamber **510**. In some implementations, in addition to and/or concurrent with the motion **540** of the cage **520** and magnetron **530** along the longitudinal axis **550**, the cage **520**, and magnetron **530** may be rotated **560** around the longitudinal axis **550**.

FIG. **6** is a flow chart illustrating a process for producing petroleum equivalent pyrolysis oil from an organic-carbon-containing feedstock in accordance with embodiments of the invention. An organic-carbon-containing feedstock, such as biomass, municipal solid waste, plant material, wood chips, and the like is input **610** to a reaction chamber having walls that are substantially transparent to microwaves used to heat and/or irradiate the feedstock. The feedstock may be a solid or a suspension that contains solid elements. The heating and/or radiation occur by directing **620** the microwave energy through the walls of the reaction chamber so that it impinges on the feedstock disposed within the reaction chamber. The feedstock is heated/irradiated **630** by the microwaves, optionally in the presence of a catalyst, until reaction of the organic-carbon-containing molecules occurs to produce the desirable end liquid fuel product. The pyrolysis oil product created by the reaction processes is collected **640**.

Various modifications and additions can be made to the preferred embodiments discussed hereinabove without departing from the scope of the present invention. Accordingly, the scope of the present invention should not be

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limited by the particular embodiments described above, but should be defined only by the claims set forth below and equivalents thereof.

What is claimed is:

1. A pyrolysis oil made using a process for converting an organic-carbon-containing feedstock mixture to the pyrolysis oil, the process comprising:

inputting the organic-carbon-containing feedstock mixture into a substantially microwave-transparent reaction chamber containing no externally supplied oxygen and within a microwave reflective enclosure;

directing microwaves from a magnetron through walls of the reaction chamber to impinge on the feedstock mixture;

rotating the magnetron around the reaction chamber; and microwaving the feedstock mixture so that the volatiles are vaporized; and

condensing the vaporized volatiles to produce the pyrolysis oil,

wherein the organic-carbon-containing feedstock comprises animal and plant material that is renewable in less than 50 years.

2. A pyrolysis oil made using the process of claim 1, further comprising mixing a catalyst with the feedstock mixture.

3. A pyrolysis oil made using the process of claim 1, wherein the pyrolysis oil has a specific gravity of less than 1.2.

4. A pyrolysis oil made using the process of claim 1, wherein the specific gravity is less than 1.2.

5. A pyrolysis oil made using the process of claim 1 having a specific gravity that is less than 1.0.

6. A pyrolysis oil made using the process of claim 1 having a pH of at least 3.0.

7. A pyrolysis oil made using the process of claim 6, wherein the pH is from 3.0 to 4.0.

8. A pyrolysis oil made using the process of claim 1 wherein the organic-carbon-containing feedstock mixture comprises at least 5 weight percent water.

9. A pyrolysis oil made using the process of claim 1 wherein the organic-carbon-containing feedstock mixture comprises at least 5 weight percent volatiles.

10. A pyrolysis oil made using the process of claim 1 wherein the organic-carbon-containing feedstock comprises feedstock mixture comprising non-renewable hydrocarbons.

11. A pyrolysis oil made using the process of claim 10 wherein the non-renewable hydrocarbons comprise coal, peat, crude oil, manufactured wooden elements, plastic, tire crumbs, or a combination thereof.

12. A pyrolysis oil made using the process of claim 1, wherein the renewable feedstock mixture comprises plant material, animal material and waste, trees, grasses, and wheat chaff.

13. A pyrolysis oil made by the process of claim 1 wherein the process further comprises shredding the feedstock mixture to a predetermined particle size.

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